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(54) In-situ endpoint detection and process monitoring method and apparatus for chemical-mechanical polishing.

(57) An in-situ chemical-mechanical polishing process monitor apparatus (50) for monitoring a polishing process during polishing of a workpiece such as a silicon wafer (52) in a polishing machine, the polishing machine having a rotatable polishing table (62) provided with a polishing slurry (61), is disclosed. The apparatus comprises a window (72) embedded within the polishing table, whereby the window traverses a viewing path during polishing and further enables in-situ viewing of a polishing surface (58) of the workpiece from an underside of the polishing table during polishing as the window traverses a detection region along the viewing path. A reflectance measurement means (74) is coupled to the window on the underside of the polishing table for measuring a reflectance. To generate a reflectance signal representative of an in-situ reflectance, wherein a prescribed change in the in-situ reflectance corresponds to a prescribed condition of the polishing process.

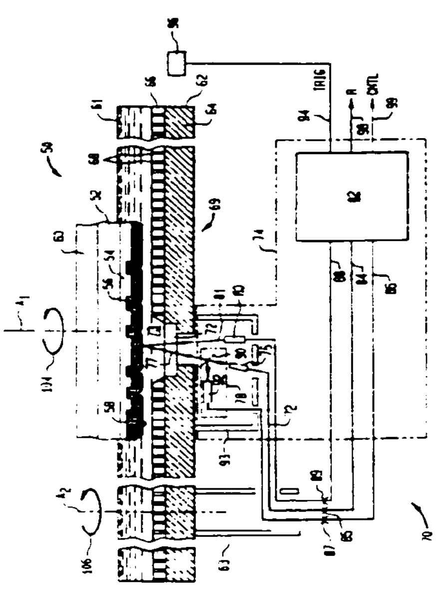

FIG. 3

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ter to edge polishing variations.

In addition to the above-noted characteristics of CMP, removal uniformity can change during polishing of a wafer as a result of changes in pad and wafer carrier conditions. Detection of abnormal removal uniformity or spurious changes therein is therefore highly desirable, i.e., a method and apparatus for in-situ detection and monitoring of removal non-uniformity.

Thus, there remains a continuing need in the semiconductor fabrication art for an apparatus and method which accurately and efficiently detects and monitors polishing characteristics of a chemical-mechanical planarization process. An in-situ real-time method and apparatus is highly desired.

SUMMARY OF THE INVENTION

An object of the present invention is to provide a in-situ real-time CMP polishing process monitor/endpoint detection method and apparatus.

Another object of the present invention is to provide a method and apparatus for CMP polishing process monitoring/endpoint detection operable over a wide range of polishing table speeds.

Yet another object of the present invention is to provide a method and apparatus for in-situ removal non-uniformity detection.

According to the invention, an in-situ chemical-mechanical polishing process monitor apparatus for monitoring a polishing process during polishing of a workpiece in a polishing machine, the polishing machine having a rotatable polishing table provided with a polishing slurry, comprises a window embedded within the polishing table, whereby the window traverses a viewing path during polishing and further enables in-situ viewing of a polishing surface of the workpiece from an underside of the polishing table during polishing as the window traverses a detection region along the viewing path. A reflectance measurement means is coupled to the window on the underside of the polishing table for measuring a reflectance, where the reflectance measurement means provides a reflectance signal representative of an in-situ reflectance, wherein a prescribed change in the in-situ reflectance corresponds to a prescribed condition of the polishing process.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing and other teachings of the present invention will become more apparent upon a detailed description of the best mode for carrying out the invention as rendered below. In the description to follow, reference will be made to the accompanying drawings, where like reference numerals are used to identify like parts in the various views and in which:

Figs. 1 and 2 are schematic representations of a VLSI wiring fabrication, including a blanket metal layer upon a dielectric layer;

Fig. 3 is a schematic view, with parts in section, of an in-situ real-time polishing process monitor apparatus in accordance with the teachings of the present invention;

Fig. 4 is a schematic top view representation of the detection region for taking in-situ reflectance measurements during each revolution of the polishing table;

Fig. 5 shows a graph of a reflectivity signal versus time in accordance with the present invention;

Fig. 6 shows a graph of in-situ reflectivity versus time in accordance with the present invention;

Fig. 7 shows a graph of in-situ reflectivity versus time in accordance with the present invention; and

Fig. 8 shows a schematic view, with parts in section, of an alternate embodiment according to the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

The invention is disclosed in connection with a chem-mech polishing apparatus or lapping machine. Because chem-mech polishing apparatus and lapping machines are well known, this description is directed in particular to elements of chem-mech polishing apparatus forming part of or cooperating directly with the invention. It is to be understood, however, that other elements not specifically shown or described may take various forms known to persons of ordinary skill in the art.

Referring now to Fig. 3, an apparatus 50 for chem-mech polishing of a semiconductor wafer or workpiece 52 having a patterned dielectric layer 54 for the subsequent formation of metal lines, contact/via studs, and/or pads is shown. A conformal metal layer 56, comprising for example aluminum, overlies the patterned dielectric layer 54 of semiconductor wafer 52. It should be noted that semiconductor wafer 52 may have been preprocessed and can therefore include layers of interleaved circuitry. For simplicity, those other features are not represented in Fig. 3.

Apparatus 50 may comprise any commercially available chem-mech polishing apparatus, such as, a Strasbaugh 6CA single wafer polisher available from R. Howard Strasbaugh Inc. of Huntington Beach, CA. Apparatus 50 includes a wafer carrier or holder 60 having a suitable means for securing wafer 52 thereto. As shown, wafer 52 is positioned between wafer carrier 60 and a polishing table 62. Wafer carrier 60 is mounted by suitable means above polishing table 62 for rotation about axis A_1 in a direction indicated by arrow 104. Wafer carrier 60 is further positionable between a polishing position and an non-polishing position by a suitable control means (not shown), accord-

a normal incident angle may be utilized with appropriate beam splitters (not shown) for directing the incident and reflected light beams as necessary.

A control means 82 provides an energization signal via signal line 84 to light source means 76 for providing the incident light beam 77 as desired. Control means 82 comprises, for example, a programmable computer or controller and appropriate interface circuitry, well known in the art, for providing the desired functions as described herein above and further below. Electrical connection between control means 82 and light source means 76 is provided, for instance, via an appropriate power cable and connections, including for example, a suitable slip-ring arrangement 85, for enabling the electrical connection to be routed through the rotation shaft spindle 63 of table 62.

Control means 82 is further responsive to the first and second light signals, provided by incident light detecting means 78 and reflected light detecting means 80, respectively, for providing a reflectance measurement therefrom. That is, control means 82 includes appropriate analog-to-digital converter circuitry for converting first and second light signals into digital signals. Control means 82 is further suitably programmed for utilizing the digital signals to effect a division of the intensity of reflected light (I) by the intensity of incident light (I_0), thereby obtaining a reflectance measurement amount R (i.e., $R=I/I_0$). First and second light signals are provided to control means 82 through signal lines 86 and 88, respectively. Signal lines 86 and 88 comprise, for instance, appropriate signal cables and connections, including for example, a suitable slip-ring arrangement, 87 and 89, respectively, for enabling the electrical connections to be routed through the rotation shaft spindle 63 of table 62.

Light source 76 can comprise a suitable light source, such as a white light or polychromatic light source, a suitable laser, a HeNe laser, a suitably collimated diode laser, or the like. The light source 76 provides a well-collimated incident light beam 77 along a corresponding incident light beam path. Typically, the beam diameter at the wafer surface comprises a beam on the order of 1 mm, but larger or smaller beams could be used depending on the spatial resolution desired. By using a large size beam, fluctuations due to pattern factor changes across a chip are reduced. The particular beam size is obtained by known methods in the art. For strongly colored slurries, the light source wavelength should be selected to minimize slurry absorption. For instance, a round trip through a 1 mm thick layer of a silica based slurry is found to attenuate a 633 nm HeNe laser beam by about 40%. The actual slurry thickness during polishing, between the wafer being polished and the window 72, is considerably smaller than 1 mm.

Incident light beam detector 78 can comprise a beam splitter 90 and a photodetector 92. Beam splitter 90 is positioned and arranged in the path of the incident light beam 77 for partially reflecting and partially transmitting the incident light beam. More particularly, beam splitter 90 comprises a suitable beam splitter for reflecting a small portion, e.g., on the order of 10%, of the incident light beam to the photodiode 92 and transmitting a bulk portion, e.g., on the order of 90%, of the incident light beam therethrough along the incident light path to the underside of window 72. The partially reflected portion of light directed onto a photodetector 92 is converted into a first signal, wherein the first signal is proportional of an amount of incident light. Photodetector 92 may comprise any suitable detector for detecting the light provided by light source 76, such as, a photodiode, for example.

As shown in FIG. 3, light source 76, incident light beam detector 78, and reflected light beam detector 80 are physically located on the underside of polishing table 62 within a suitable protective cover 93. Protective cover 93 prevents undesirable contamination of the light source and photodetectors. The inside surface of the protective cover 93 can be coated with a non-reflective coating, such as, with a flat black paint, to reduce light scattering effects within the same.

A trigger input 94_{TRIG} of control means 82 is electrically connected to a position detection device 96. Position detection device 96 can comprise any suitable means for providing a signal indicative of a pre-established positional relationship between the wafer carrier 60, and thus the wafer 52 being polished, and the window 72, to be discussed further hereafter below with reference to a detection region. A trigger signal received by trigger input 94_{TRIG} instructs control means 82 to perform a desired operation responsive to the first and second light signals on signal lines 86 and 88, respectively, for producing a reflectance signal R. The reflectance signal so generated is output on signal line 98. The trigger input 94_{TRIG} described above is illustrative and not meant to preclude the use of other triggering means. For instance, control means 82 can be self-triggering whereby overlap of the wafer with the window is detected by a sudden change to a reflectance higher than that of the bare window.

Control means 82 receives incident and reflected light signals as discussed above and converts the same into a cognizable form, such as a real-time graph similar to the graph as shown in FIG. 5, for use by an operator of the CMP apparatus or for automatic control purposes as further discussed hereinbelow. For example, control means 82 may include a display means for real-time display of polishing process data of a desired polishing process condition, such as, a polishing endpoint, during the polishing of wafer 52 by CMP apparatus 50. Preferably, the endpoint data is determined from a prescribed change in reflectance during polishing from an initial reflectance, corre-

control means 82 by suitable well known programming of control means 82, using commercially available software, for example, QBASIC, as sold by Microsoft Corporation of Redmond, WA. FIG. 5 shows a simulation of the reflectance as a function of time for two wafer positions. In the first position (dashed trace), the Al is deposited over bare, unpatterned silicon. In the second position (solid trace), the Al film is deposited over an array of silicon trenches of equal linewidth and spacing. The initial reflectivity at both positions will be around 90%, corresponding to a blanket Al surface. The reflectivity at the polishing endpoint will be close to 35% for position 1 (the reflectivity for bare silicon) and near 65% for position 2 (approximately the area-weighted average of the Al and Si reflectivities). The presence of the slurry and/or an additional dielectric layer in the wafer will slightly alter these values, which were computed for a wafer/air interface. The plot of data points in the Fig. 5 can comprise data points averaged over 3 revolutions (i.e., running average), thereby improving a signal-to-noise ratio. Any noise component of the data can reasonably be smoothed out considerably by this averaging procedure as performed by control means 82.

Simulated output signals of reflectance versus time are shown in FIGS. 6 and 7, as monitored using a digital oscilloscope, for example. FIG. 6 is representative of uniform removal of a metal layer 56. FIG. 7 is representative of a non-uniform removal of a metal layer 56, that is, corresponding to an instance in which the metal layer 56 is cleared away from the edge portions of the wafer before being cleared away from the center portion of the wafer. The parameters used for the determination of a polishing process condition, such as polishing end point and/or polishing non-uniformity condition, by apparatus 70 can be calibrated for every level to be polished, or pre-set values corresponding to the type of material being polished and the pattern factor of the underlying layer, may be used. Once this calibration is performed, a prescribed change in the reflectance will correspond to the polishing endpoint or polishing non-uniformity condition for the given VLSI structure.

Referring again to FIGS. 6 and 7, the in-situ removal monitoring aspect of the present invention will be further explained. A typical reflectance output signal is schematically represented which includes pulses 120 and 122, respectively. Reflectance pulses 120 and 122 are reflectance signal pulses obtained or produced by control means 82 for multiple passes of the window 72 under wafer 52. The reflectance pulses 120 and 122, respectively, are separated in time by a time distance T between the pulses corresponding to the rotation period of the polishing table 62. Each pulse can be analyzed in terms of five (5) different regions: region A is a pre-measurement signal region, region B is a rising signal region, region C is a steady state signal region, region D is a fall off region, and lastly, region E is a post measurement signal region.

The magnitude of the pre- and post-measurement signals contained in regions A and E, respectively, are independent of time and therefore do not contain information about the film layer of the wafer being polished. Upon movement of window 72 along path 105 and completely under wafer carrier 60, only a very thin layer of slurry is present between the wafer and the window. Regions B and D, as shown in FIGS. 6 and 7, correspond to the window being in region 107_B and 107_C of FIG. 4, respectively. Region C corresponds to the window 72 being under the center region of wafer 52 along path 105.

A lead, center, and trailing edge reflectance measurements may be analyzed in a prescribed manner by control means 82 for real-time monitoring of the polishing of the lead, center, and trailing edge portions of the polished surface 58. An indication of polishing uniformity can easily be detected therefrom, for instance, from variations observed in successive measurements of the wafer's lead edge and center reflectances. Other reflectance measurement comparisons can be made also.

With respect to regions B, C, and D of FIG. 7, different portions thereof correspond to reflectance data from different locations across wafer 52. That is, the magnitude of the reflectance signal is indicative of the presence or absence of the undesired bulk portion of layer 56 across wafer 52. Thus, by inspecting pulse 120 or any subsequent pulses, information about the removal uniformity can be obtained in-situ. In particular, the reflectance amplitude across the pulse in regions B, C, and D can be analyzed by control means 82 for detection of any significant rate of change in the signal beyond a prescribed amount for any one particular pulse. That is, if the rate of change in magnitude exceeds a prescribed amount, corresponding to non-uniformity of removal of material from the polishing material, control means 82 can thereafter provide an indication of such removal non-uniformity, such as, via control signal CNTL on signal line 99, and the polishing process can be modified appropriately. Polishing tool parameters can be modified, manually or automatically, so as to compensate for the detected non-uniformity. As shown in Fig. 7, the signal output is representative of non-uniform polishing conditions wherein the undesired metal was polished away from regions on the wafer corresponding to B and D, while remaining on the wafer in a region corresponding to C. This is an example of the case where the removal rate at the wafer edges is greater than the removal rate at the center of the wafer. Criteria, suitable for a particular polishing operation, can be established as appropriate for an acceptable in-situ non-uniformity set point, i.e., the point at which polishing conditions are modified or terminated due to excessive non-uniform polishing.

In an alternate embodiment, as shown in FIG. 8,

FIG. 1

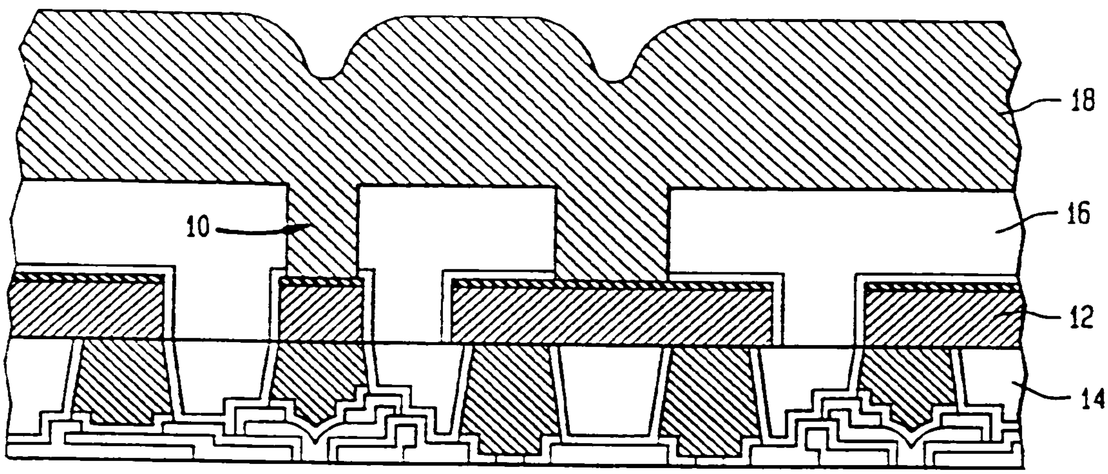


FIG. 2

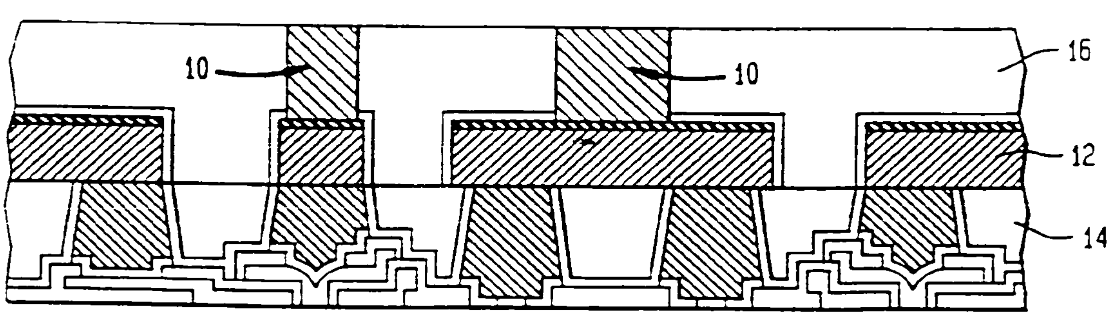


FIG. 4

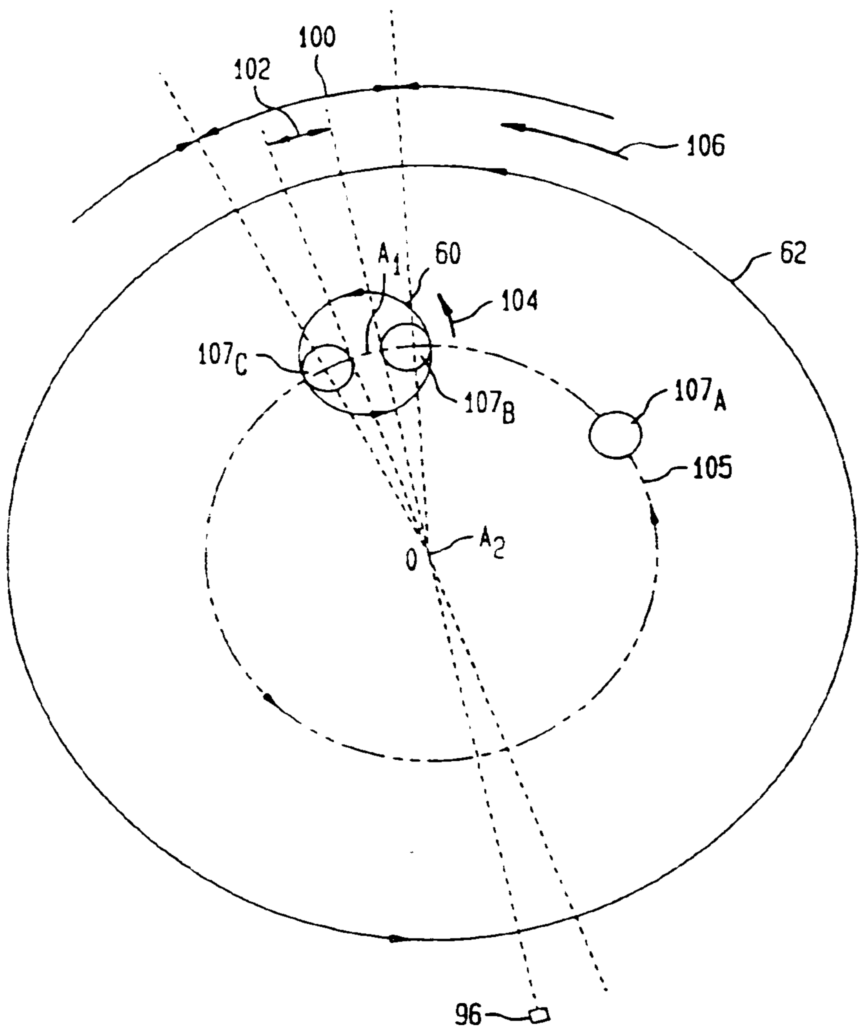

100
102
106
62
A_1
60
104
107_C
107_B
107_A
105
0
A_2
96

FIG. 5

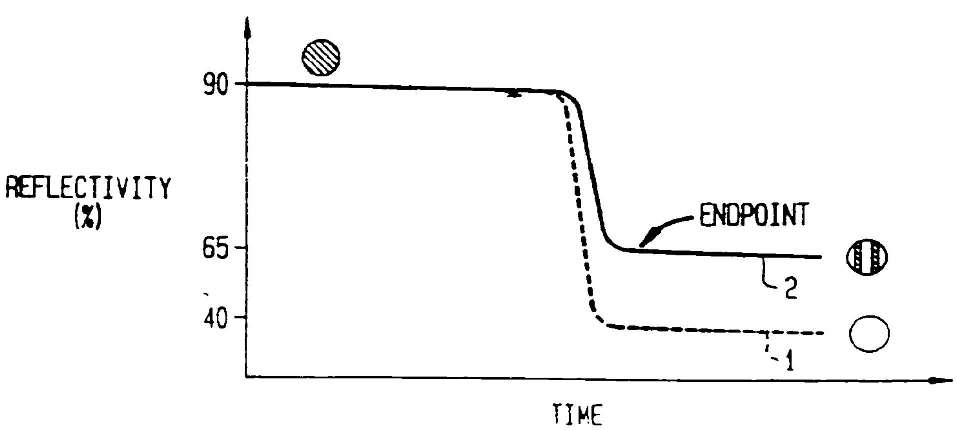
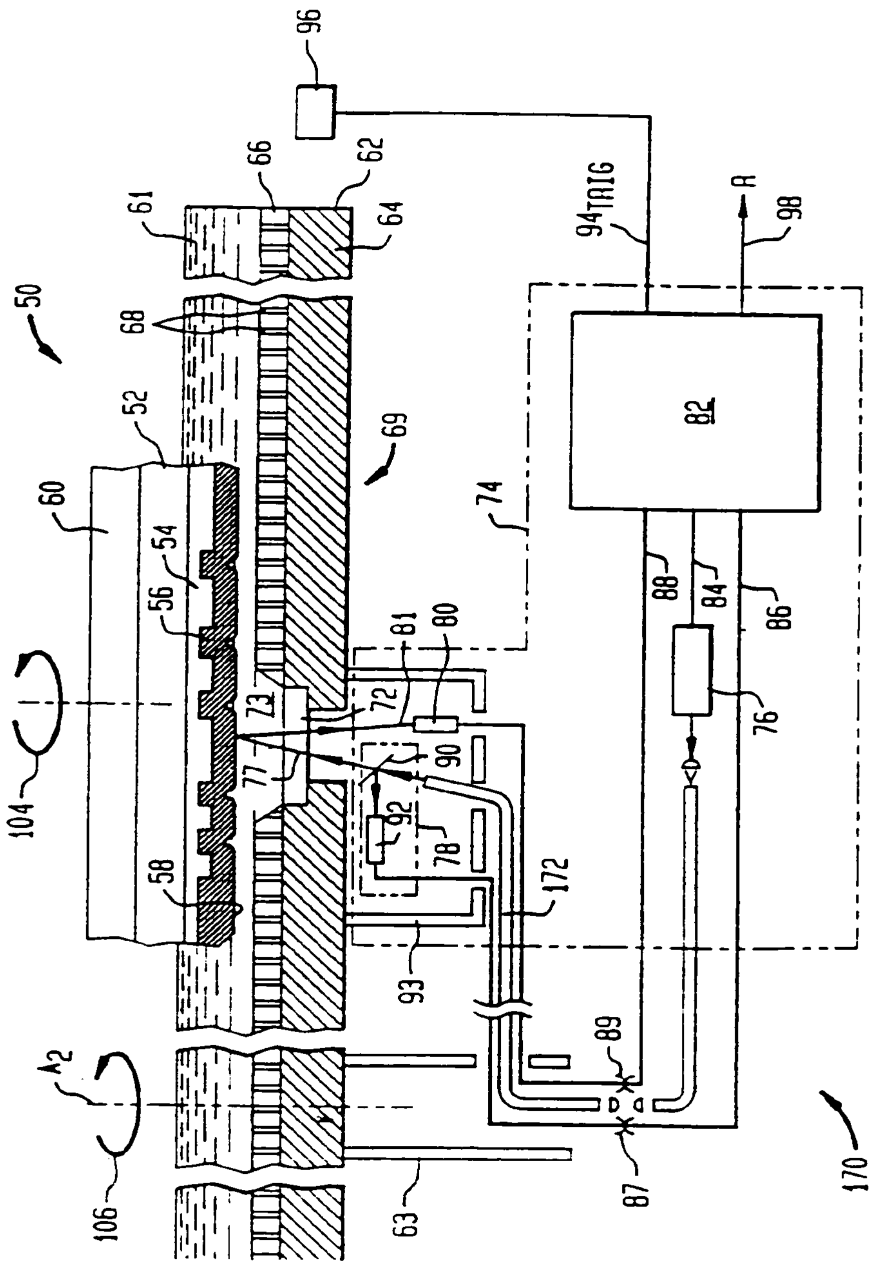

90
REFLECTIVITY (%)
65
40
ENDPOINT
2
1
TIME

FIG. 8


P
A1
104
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172
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94 TRIG
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84
86
76
89
87
170
A2
106
63